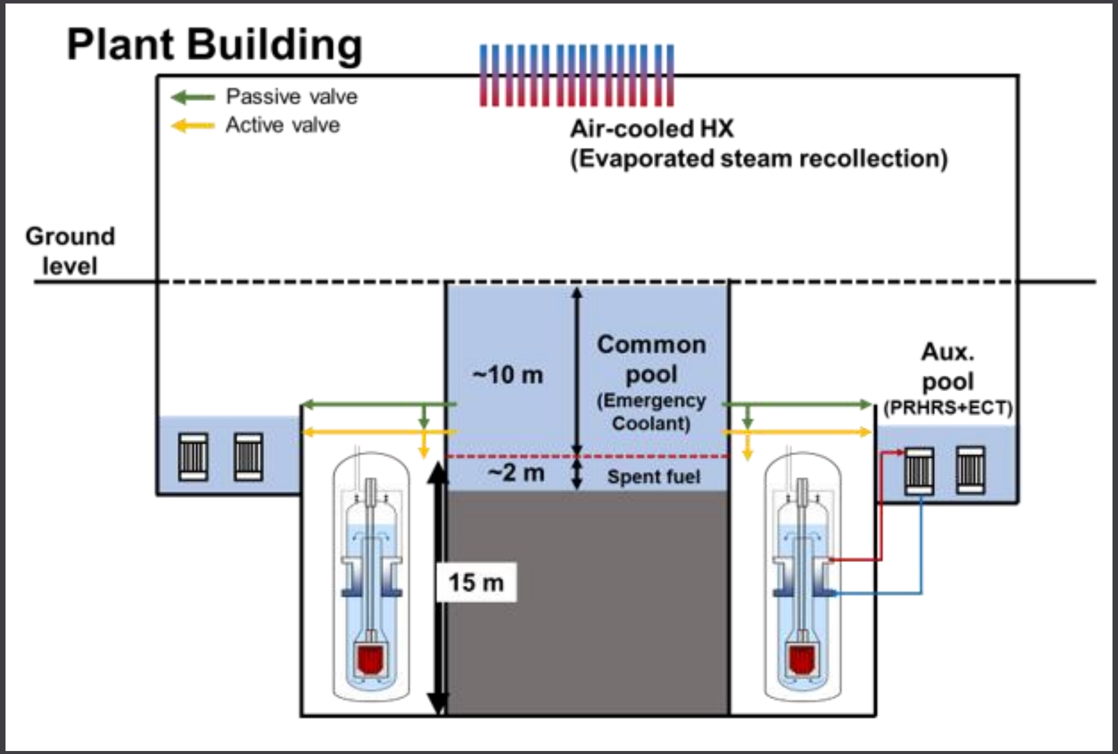
Feasibility analysis of flooding safety system of ATOM during early phase of accident by using MELCOR code



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Department of Nuclear Engineering, Hanyang University

PRESENTATION DATE: 2022.10.21

LOCATION: Korean Nuclear Society Autumn meeting

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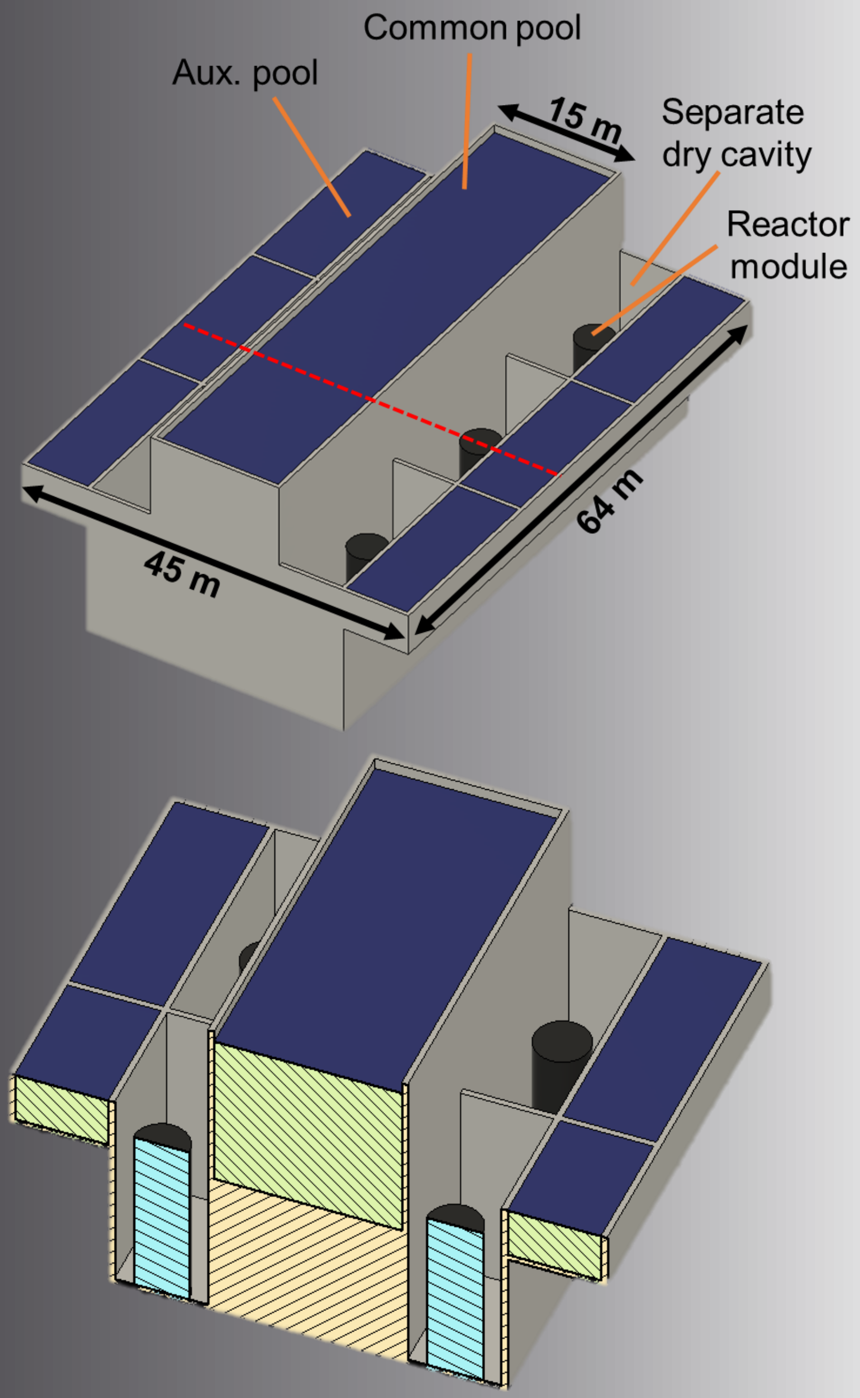


Common pool
Aux. pool
15 m
Separate dry cavity
Reactor module
64 m
45 m

Small Modular Reactor (SMR)

SMART

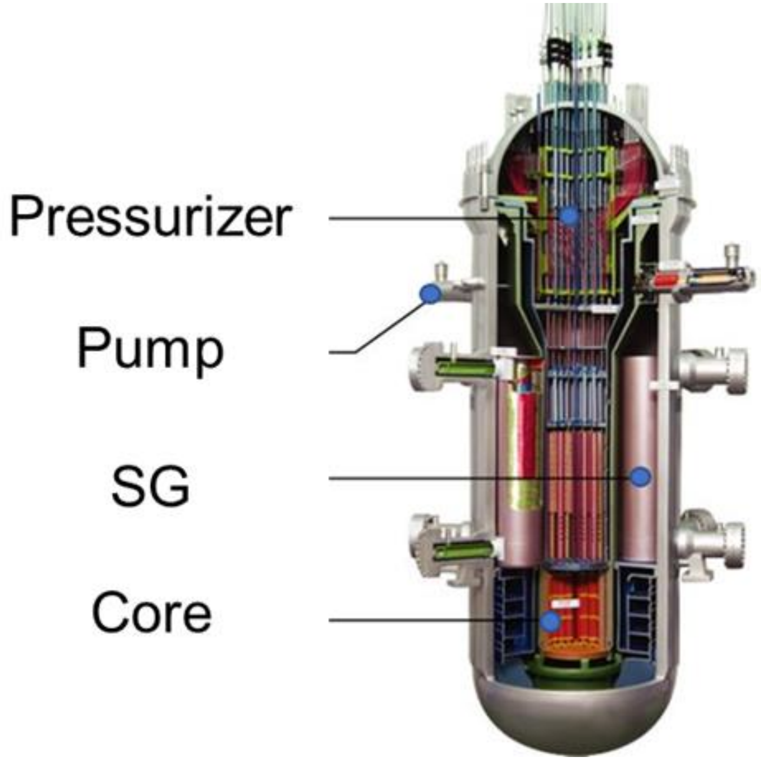


*Figure source: KAERI

Characteristics

- Small
- Modularization
- Integration
- Simplification

Advantages

- Site flexibility
- Multi-utilization
- Enhanced safety

- No risk of LBLOCA
- Low thermal power output
- **Fully Passive safety system**

1) Locatelli, Giorgio, Chris Bingham, and Mauro Mancini. "Small modular reactors: A comprehensive overview of their economics and strategic aspects." Progress in Nuclear Energy 73 (2014): 75-85.

Introduction

Passive safety system of SMR

- Integration
- Small
- Simplification

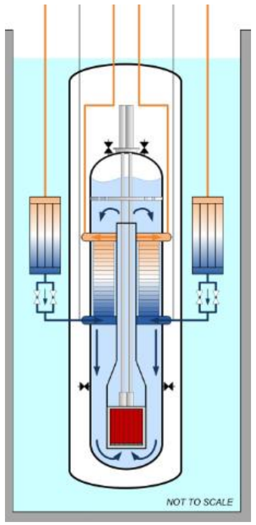
→

- Low thermal power
- Low pressure drop

→

Passive safety system

- No active system
- Low driving force



NuScale SMR

- Thermal power 200 MWth
- 12 modules in a building
- **ECCS, DHRS**
  → Indefinite grace period

ATOM

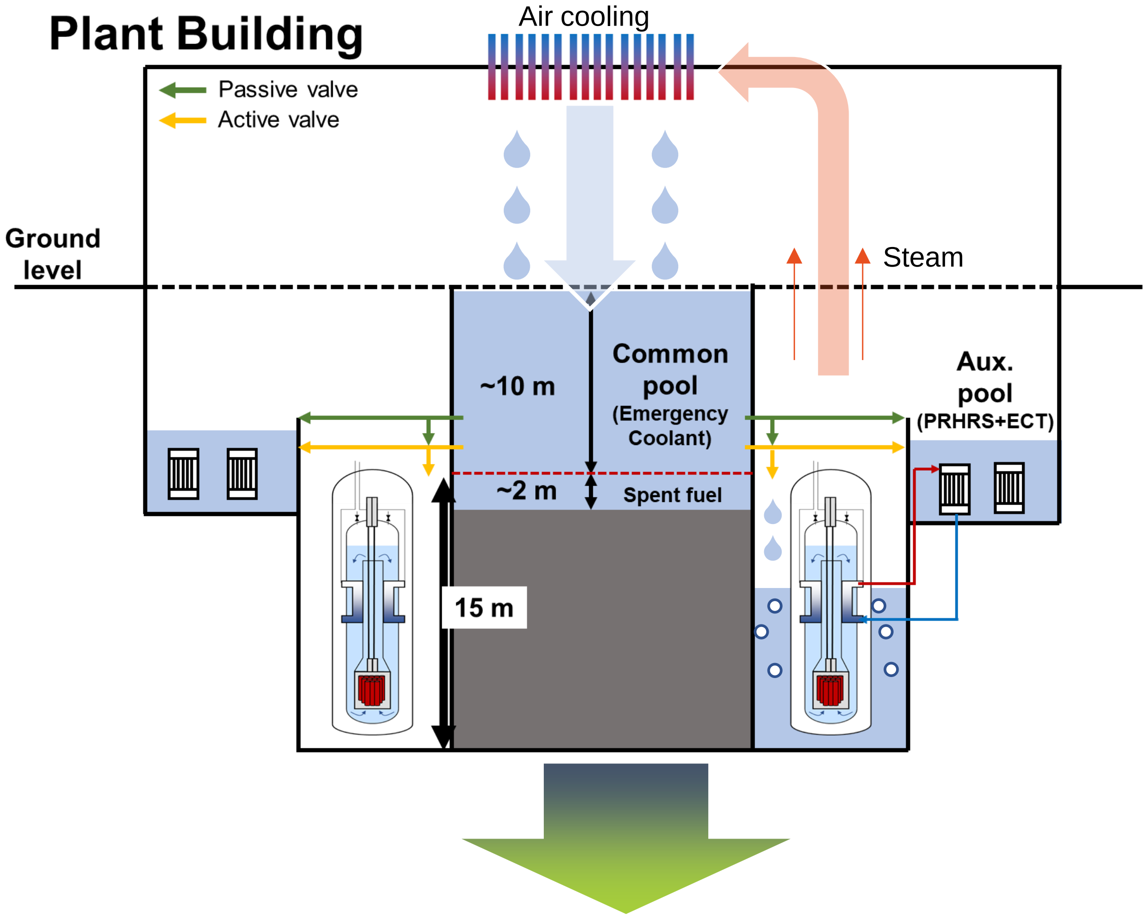
- Thermal power 330 ~ 450 MWth
- 6 modules in a building
- **PRHRS, FSS**

1) Locatelli, Giorgio, Chris Bingham, and Mauro Mancini. "Small modular reactors: A comprehensive overview of their economics and strategic aspects." Progress in Nuclear Energy 73 (2014): 75-85.

Objective of flooding safety system

Objective

- Flooding system
- Separated cavity
- Long-term coolability



Enhanced long-term safety!

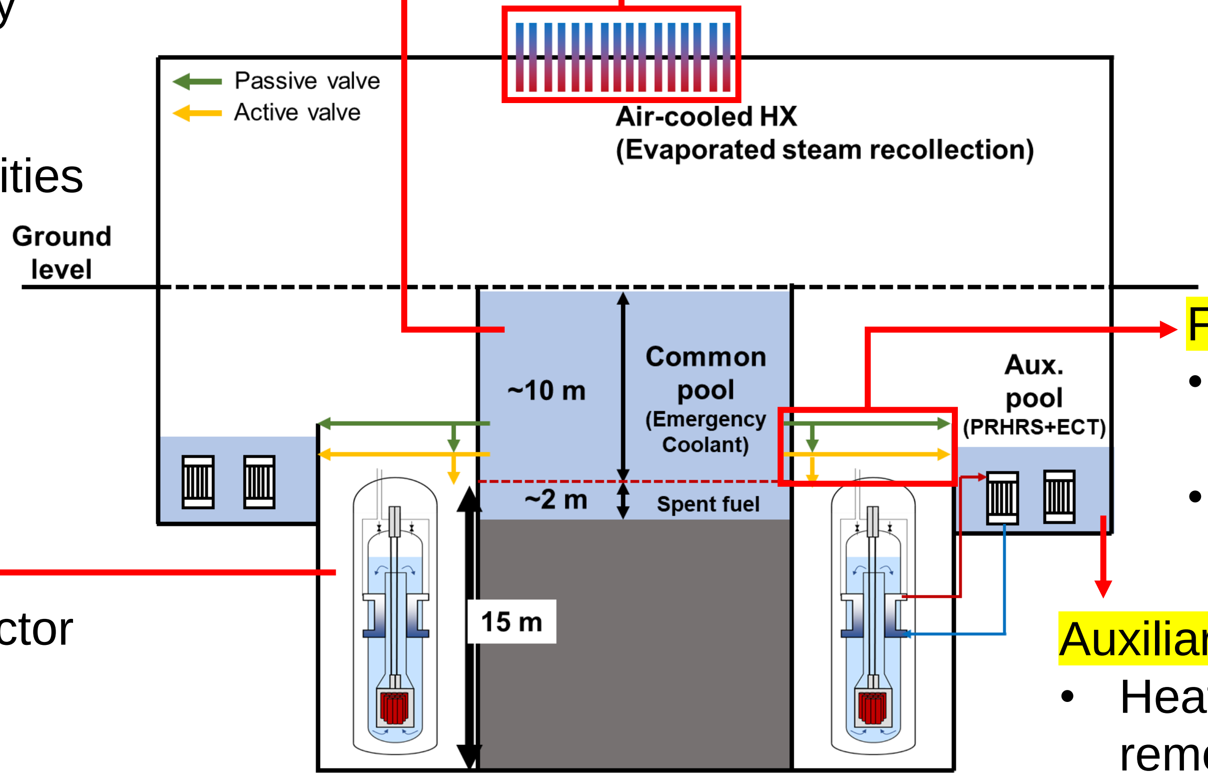
Flooding safety system (FSS)

Common pool (CP)

- Centralized coolant inventory
- Storage of spent fuel
- Sufficient volume to supply emergency coolant to 6 cavities

Condensation system

- Condenses vaporized coolant to re-collect extra coolant into the CP



Flooding valve

- Coolant supply to cavity and Aux. pool
- Passive/Active operation

Separate dry cavities

- Containing single reactor module
- Volume is 1,568 m^3

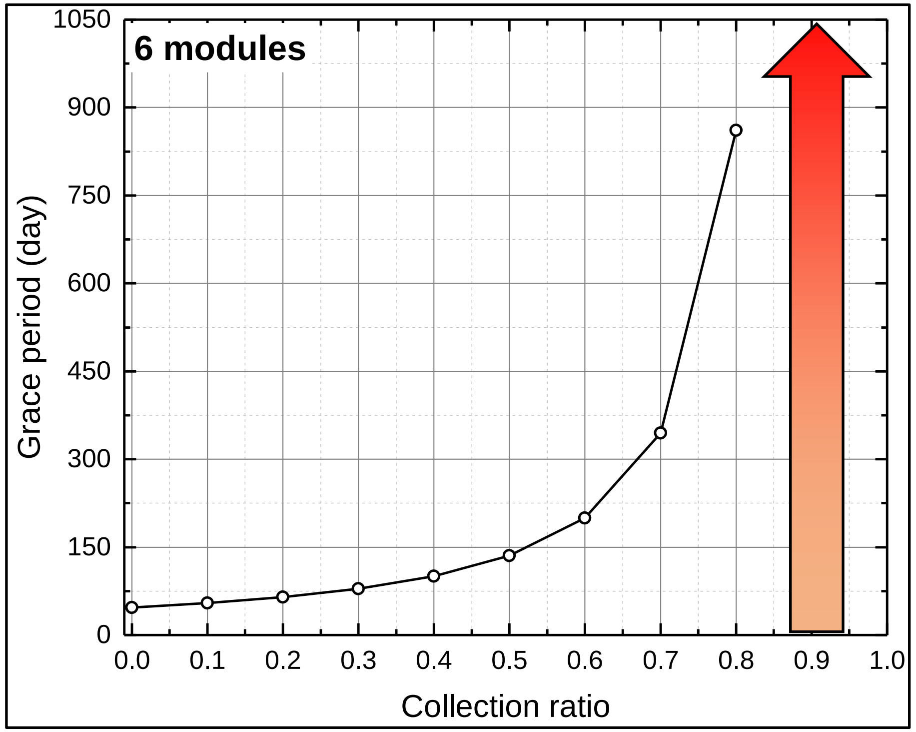
Auxiliary pool

- Heat sink of passive residual heat removal system (PRHRS)

Introduction

Validation of FSS

Long-term coolability

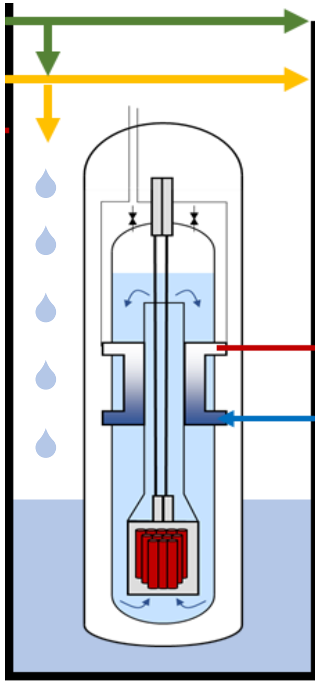


Grace period with partial re-collection ratio

Limitation

- ✓ Immediate flooding was assumed

Early phase core integrity



Flooding time

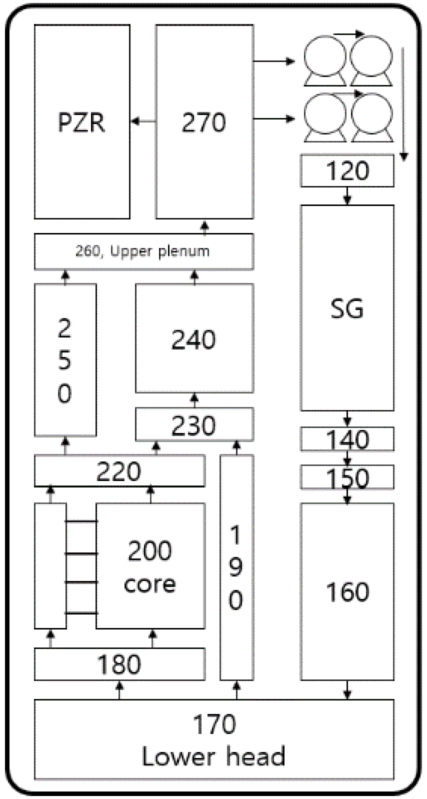
- ✓ Sufficiently short to sustain core integrity

Flooding valve

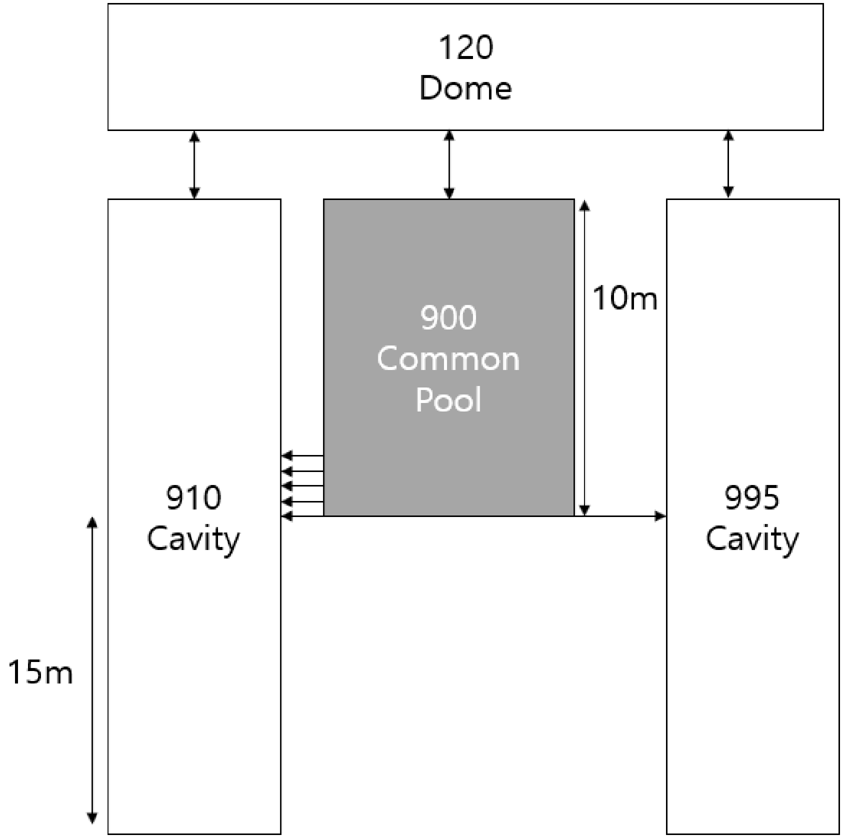
- ✓ Meet the objective flooding time

Introduction

Objective



Core uncovery time



- 330 MWth ATOM MELCOR input model
- **Estimate core uncovery time**

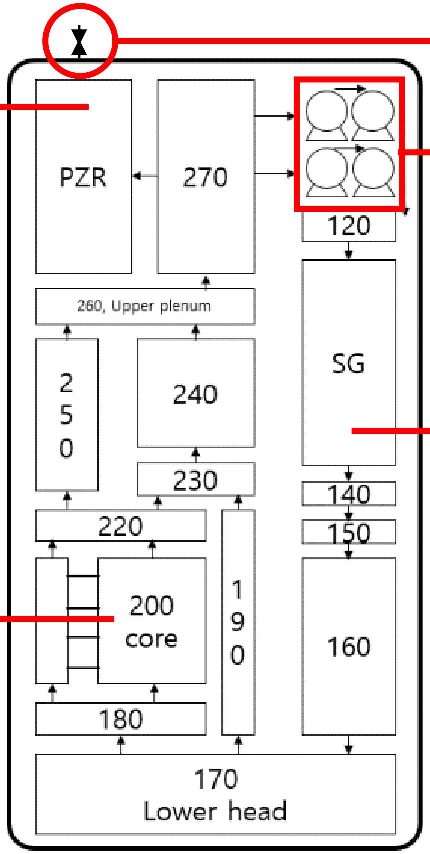
- Flooding safety system MELCOR input model
- **Investigation of requirement of flooding path to prevent core damage**

330 MWth ATOM

*ADS; Automatic depressurization system

Pressurizer
- System pressure: 15 MPa

ADS ventilation valve
- Actuates to relieve overpressure of RPV
- Flow area: 1.0134×10^{-4} m^2
- Opening pressure: 17.4 MPa



Reactor coolant pump

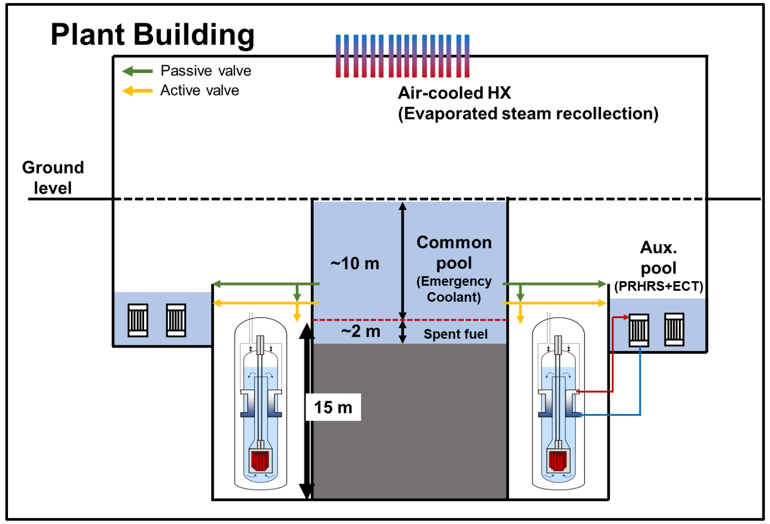
Core
- Thermal power: 330 MWth
- Diameter: 2.125 m

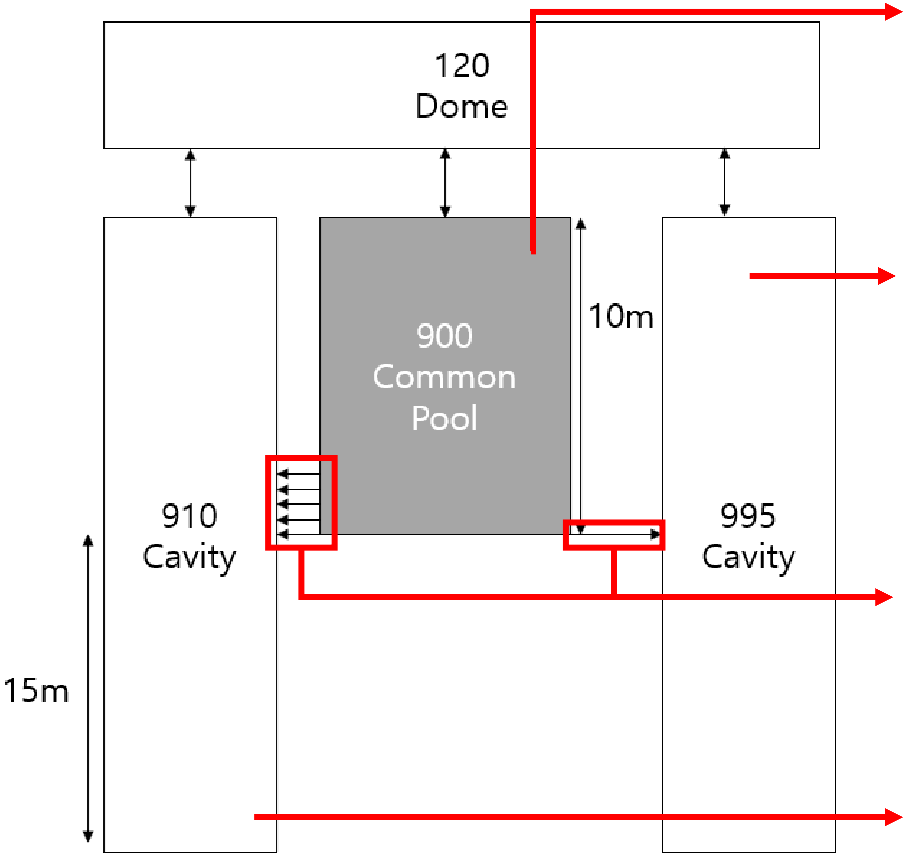
Steam generator
- Connected to 2nd system
- Helical SG

×6 modules in a plant building

Methodology

MELCOR nodalization of FSS





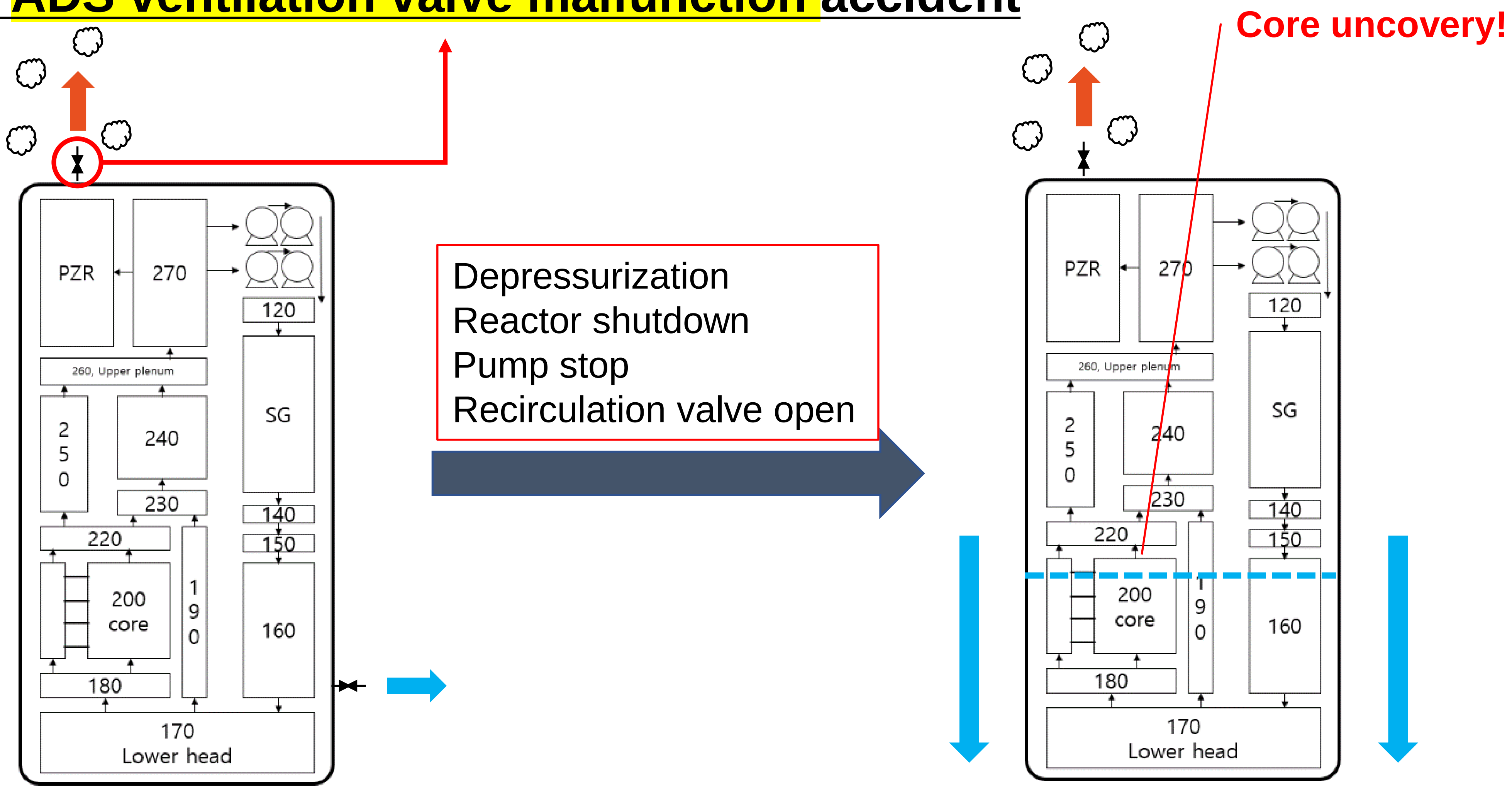
Common pool
- 10 m high
- 9,408 m^3 of emergency coolant

Cavity - CV995
- Volume for single cavity, single valve
- Volume: 1,568 m^3
- 15 m below of the flooding valve

Flooding valve
- Form loss coefficient = 1.5
- Assumed simple, pipe-like structure

Cavity - CV910
- Volume for 5 cavities, 5 valves
- Volume: 7,840 m^3

Scenario: ADS ventilation valve malfunction accident



Methodology

Flooding time simulation matrix

*6 cavities flooding assumed

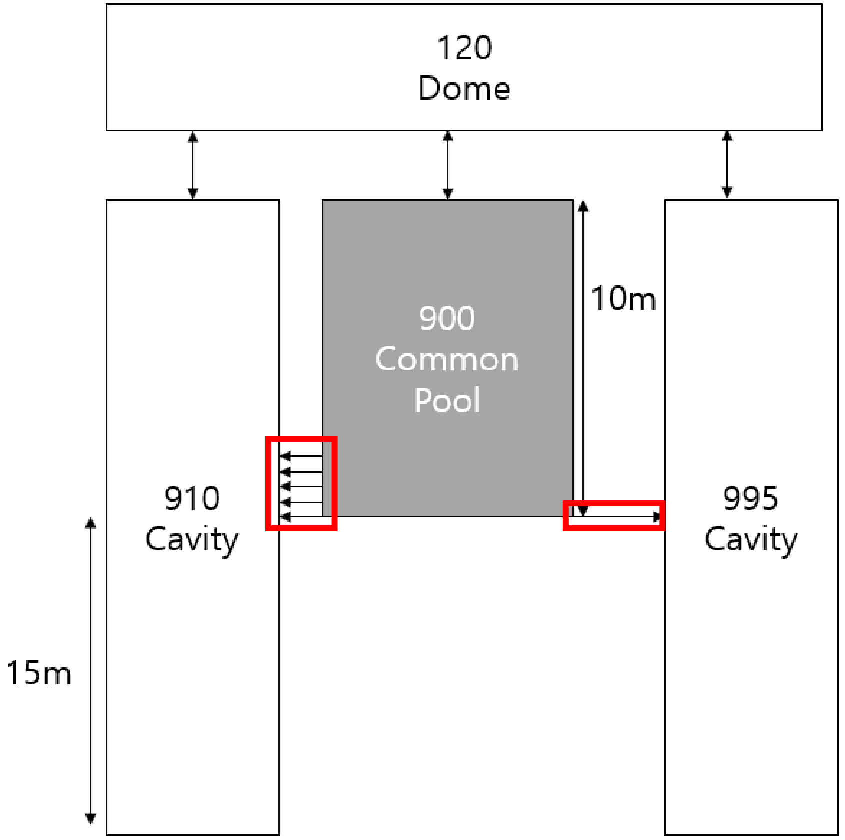


*Figure with single valve per each cavity

Simulation variables

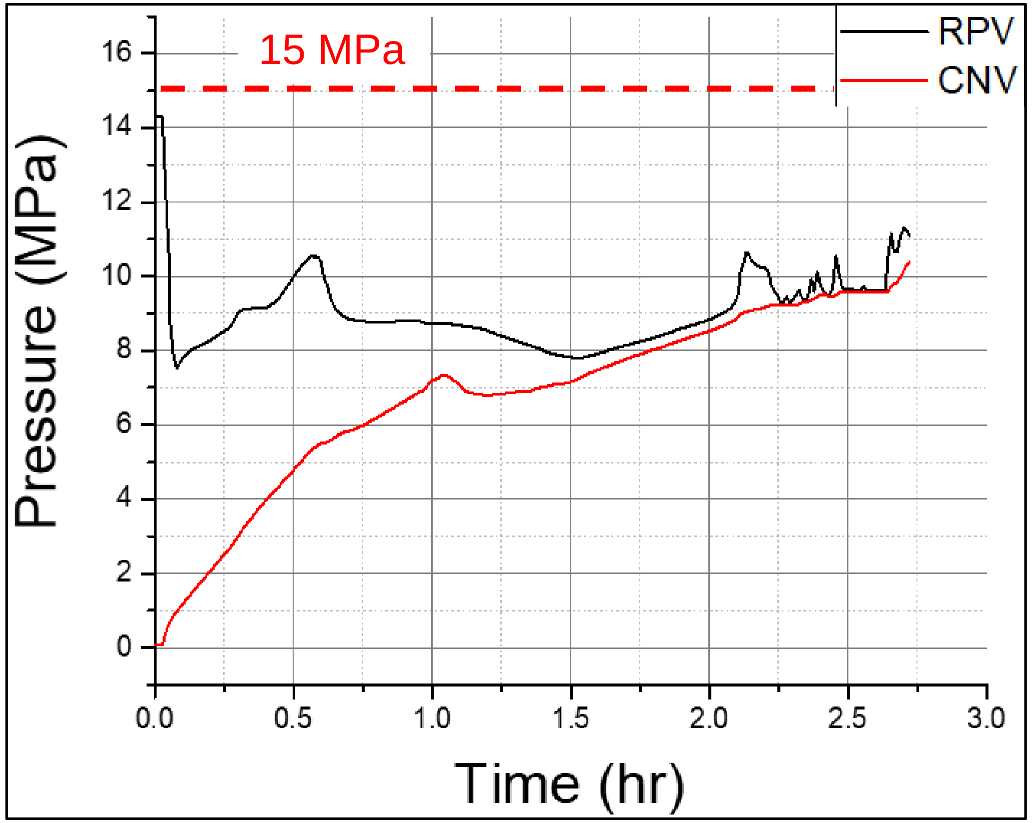
- Valve flow area
  - Dominant parameter to flooding time
- Number of valves
  - Effect of multiplicity

Flow area (m^2)	0.02	0.04	0.06	0.08	0.1
Number of valves *	1	2	3	4	5

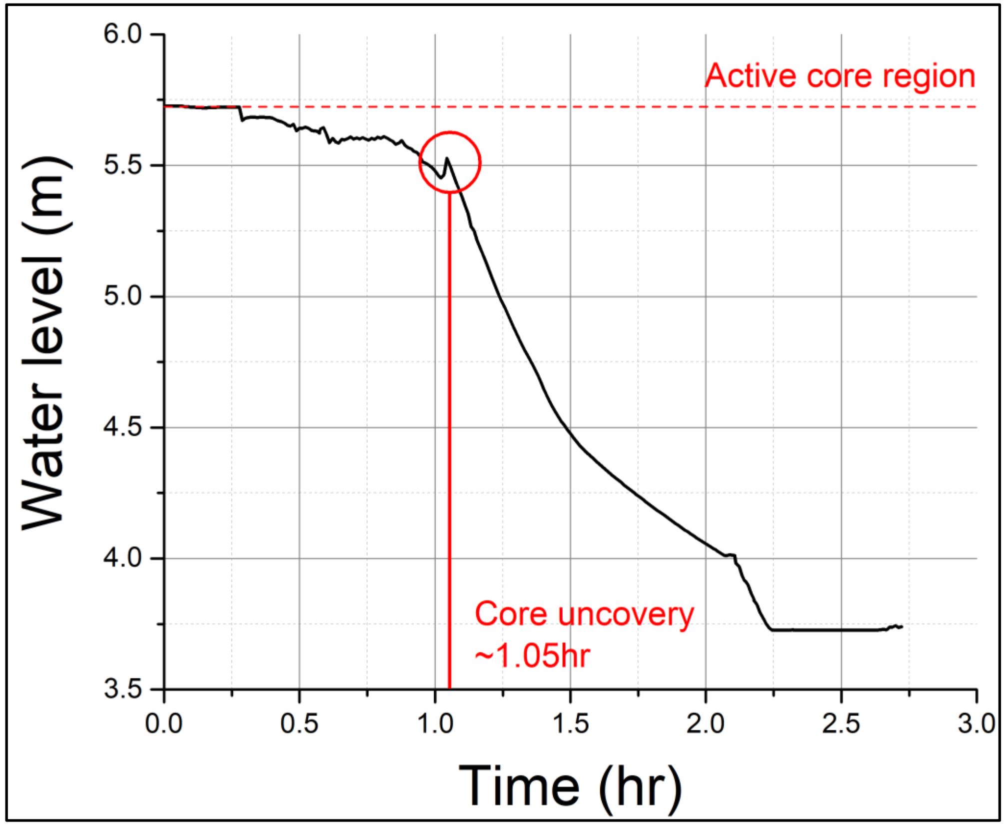
* per each cavity

Results and discussion

Core uncovery time



System pressure



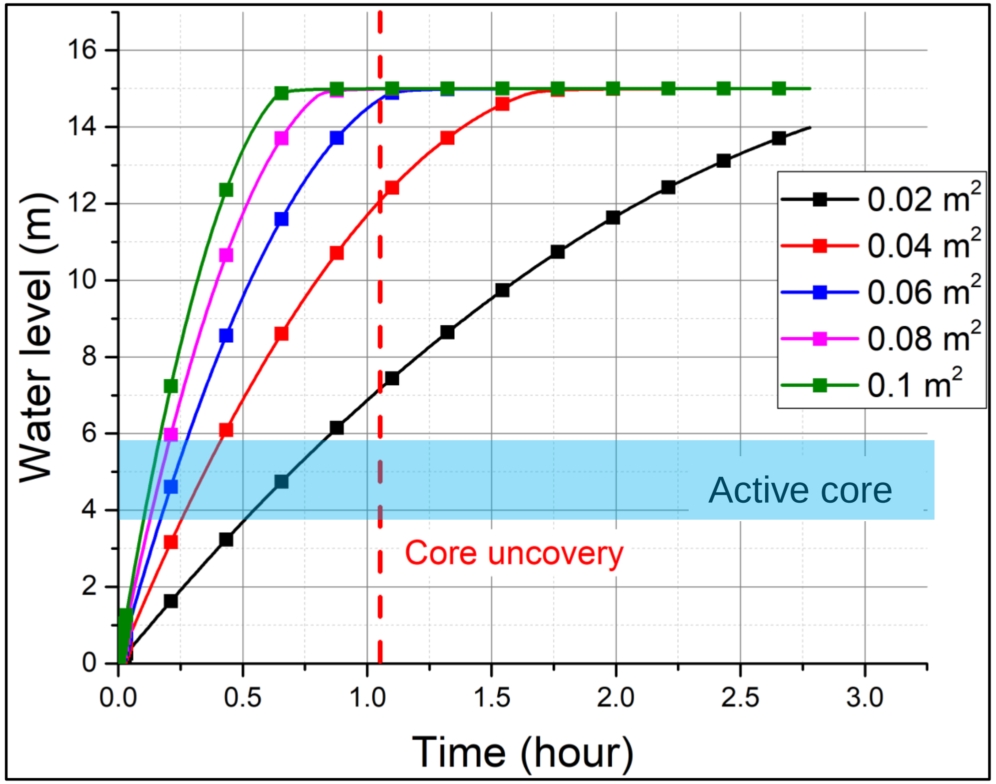
Core water level

- Rapid RPV pressure decrease after the accident
- **Core water level started to decrease 1.05 hour after**

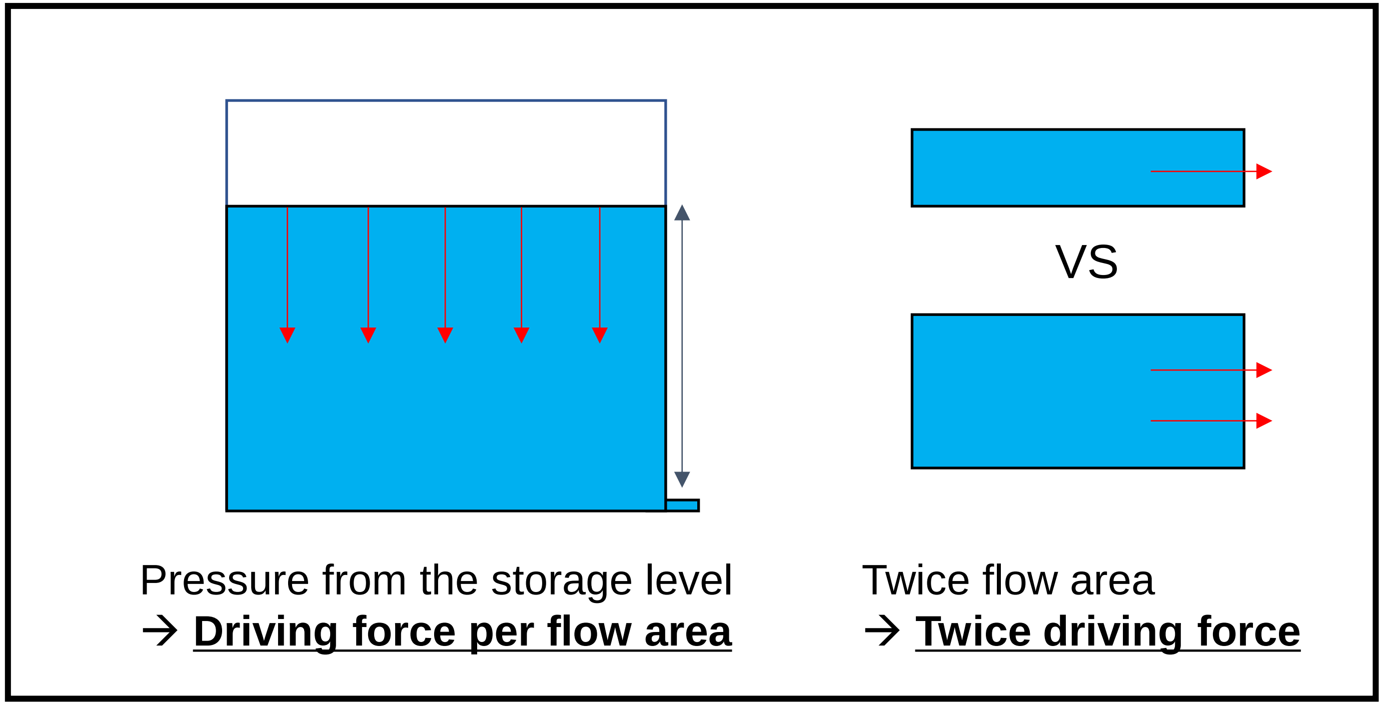
Core uncovery

Cavity flooding time with valve flow area

Variable 1: flow area



Cavity water level with flow area of the valve

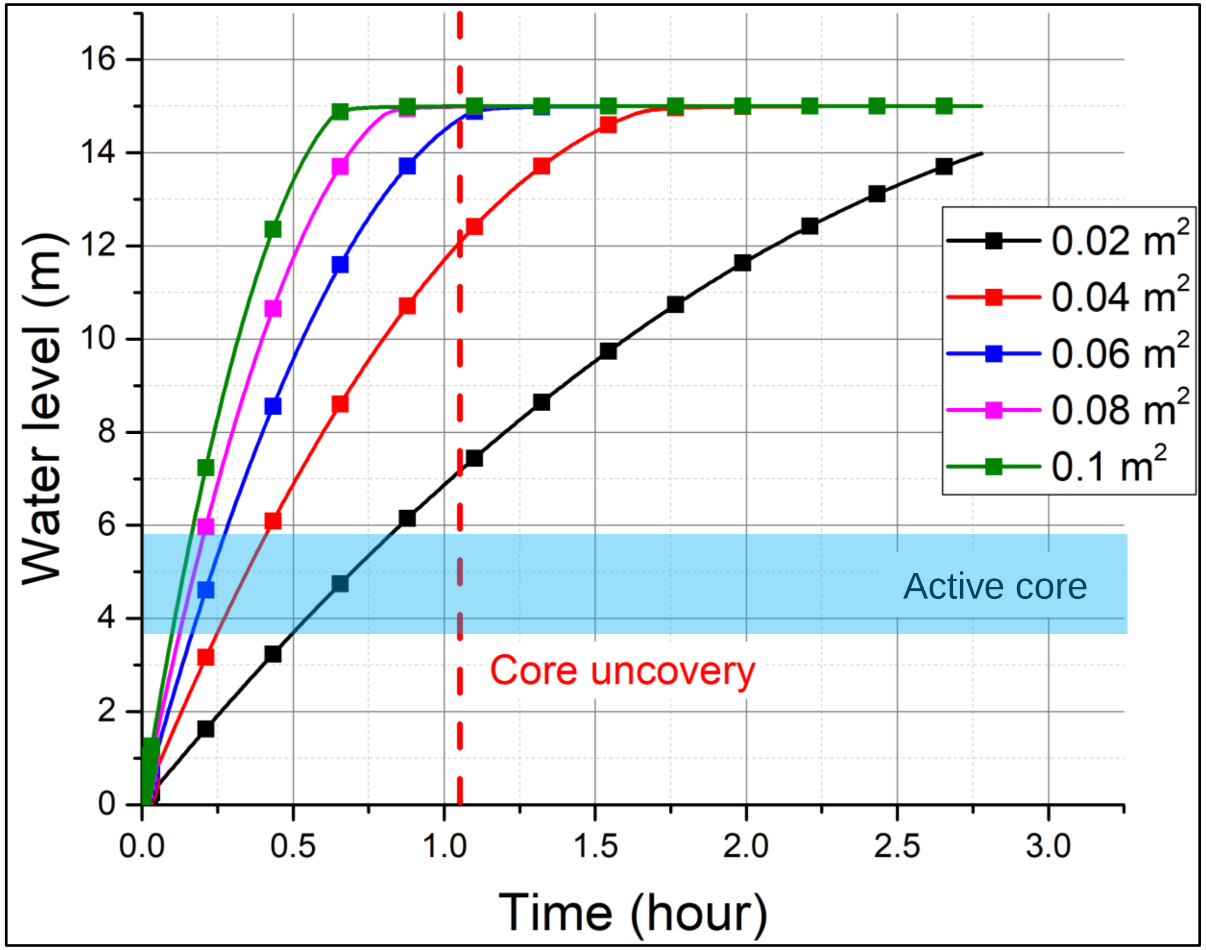


1. Gradually decreasing flow rate
2. Inversely proportional flooding time to flow area

Linearly proportional flow rate to flow area
→ **Inversely proportional flooding time**

Cavity flooding time with valve flow area

Variable 1: flow area



Cavity water level with flow area of the valve

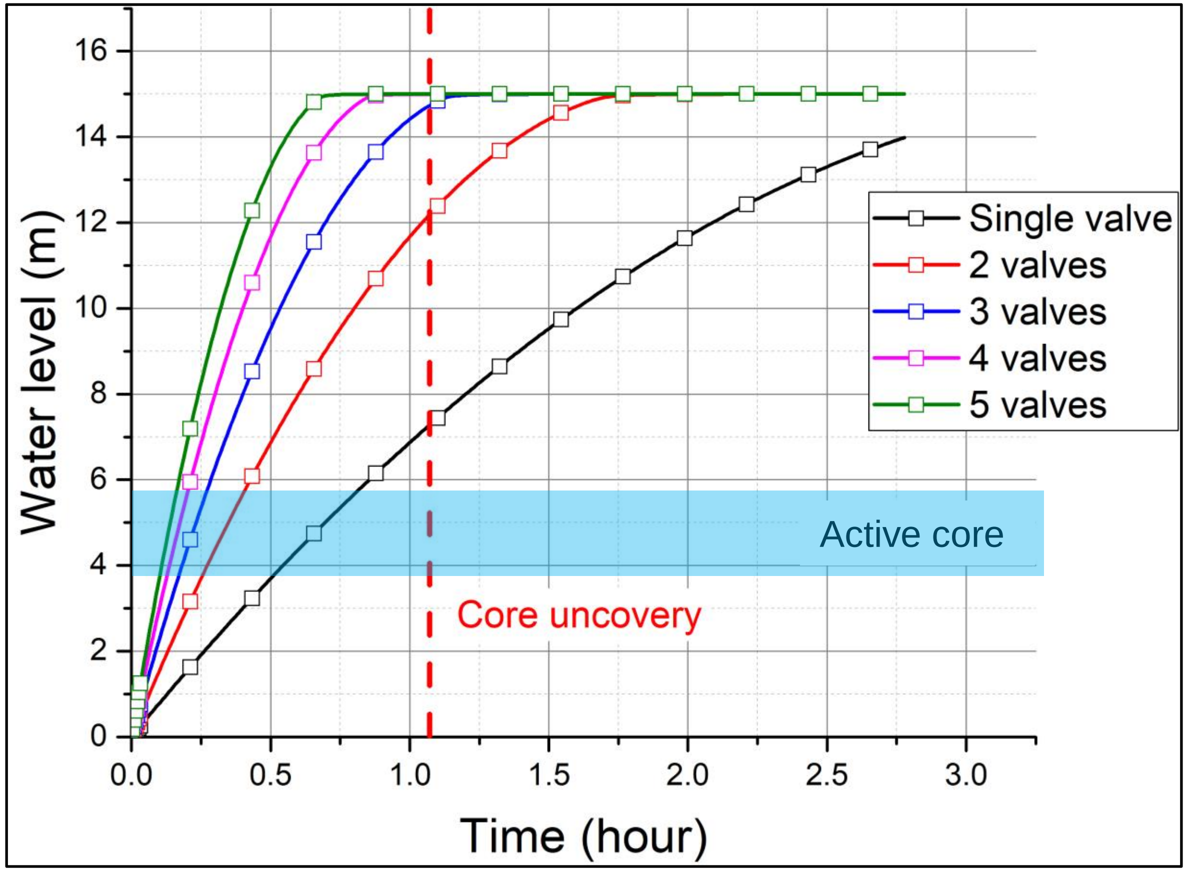
Flow area (m^2)	0.02	0.04	0.06	0.08	0.1
Core level reached (hr)	0.81	0.40	0.27	0.20	0.16
Fully submerged (hr)	NA	1.68	1.11	0.83	0.67

- Flow area 0.02 & 0.04 m^2 → insufficient flooding time
- Flow area 0.08 & 0.1 m^2 → sufficient flooding time
- Flow area 0.06 m^2 → closer investigation is needed!

Results and discussion

Cavity flooding time with the number of valves

Variable 2: Valve #



Cavity water level with the number of valves

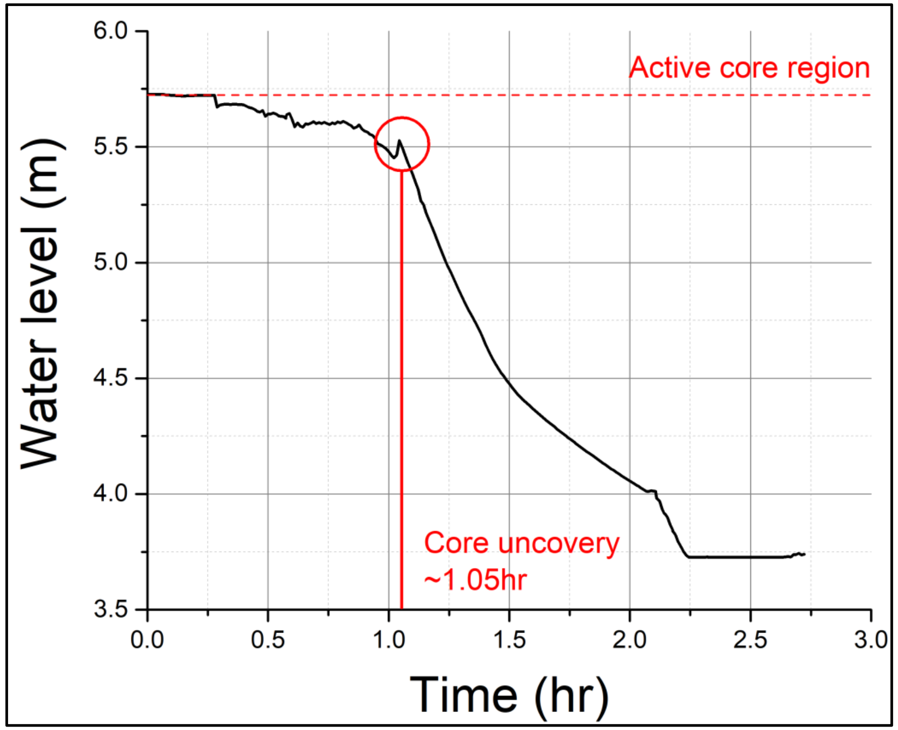
- Each valve has flow area 0.02 m^2
- Approximately **0.01-hour delay** from the **identical total flow area case**
- Reason of the delay
  → **extra pressure drop** from smaller flow area

Flow area (m^2)	0.02	0.04	0.06	0.08	0.1
Core level reached (hr)	0.81	0.40	0.27	0.20	0.16
Core level reached delay (hr)	NA				
Fully submerged (hr)	NA	1.69	1.12	0.84	0.68
Fully submerged delay (hr)	NA	0.012	0.011	0.011	0.01

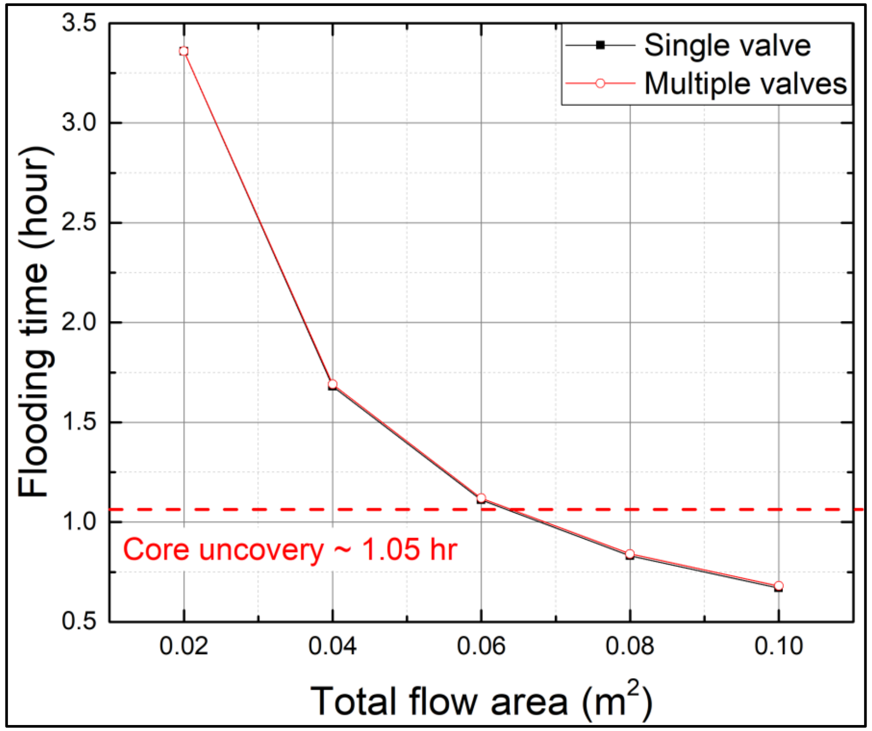
→ **Replacement of single large valve with multiple valves can be achieved**

Conclusion

Summary



Core water level



Flooding time with total flow area of valves

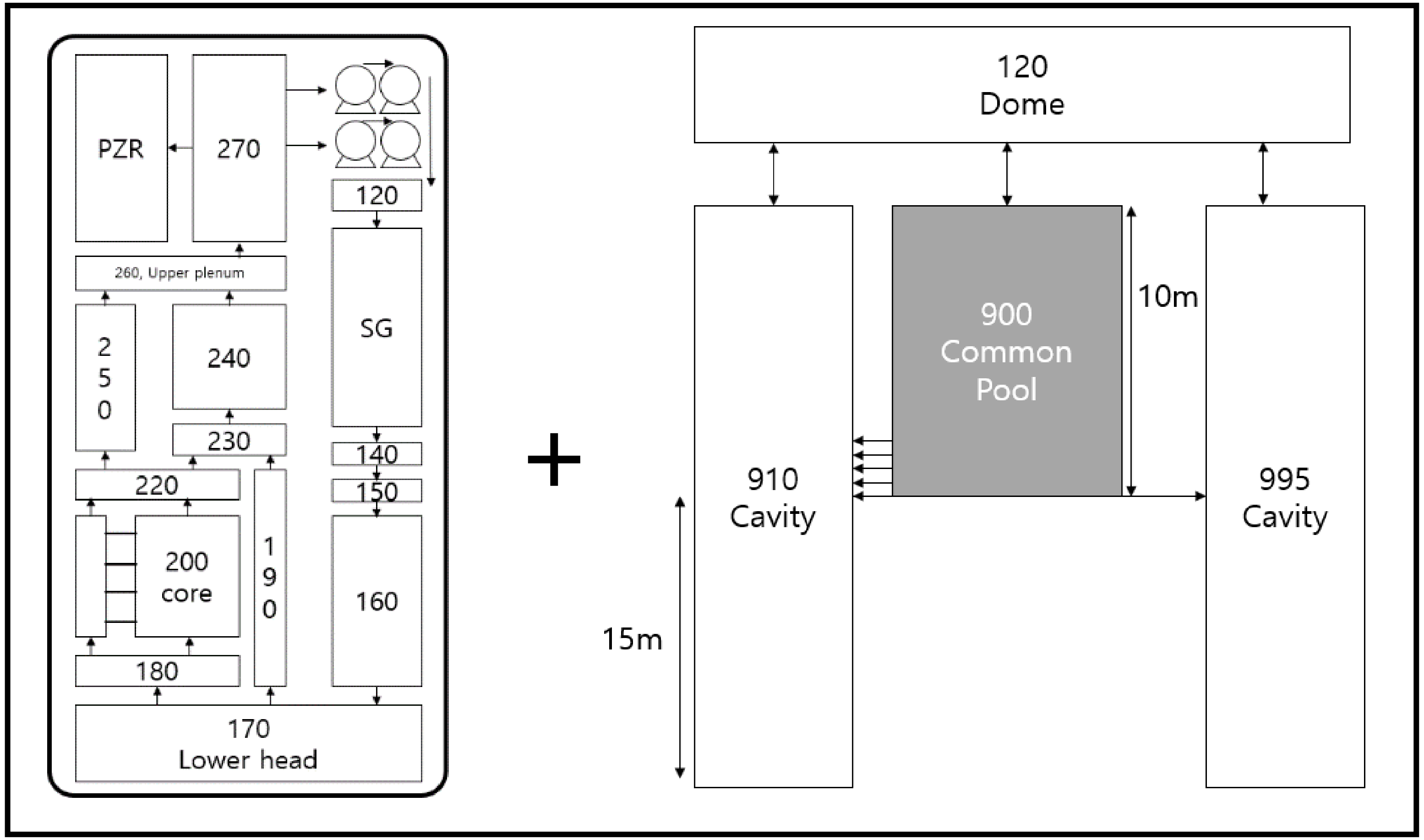
- Core uncovery time evaluation of 330 MWth ATOM
- ADS ventilation valve malfunction accident
- **Core uncovery at 1.05 hour after the accident**

✓ **Total flow area larger than 0.06 m^2 → met the time limit**

✓ **Multiplicity from multiple valves → achievable!**

Future work

Integrated analysis of FSS short-term coolability



Integrated SMR + FSS input model

Severe accident analysis using MELCOR code

Detailed analysis of flooding effect on core level sustainment

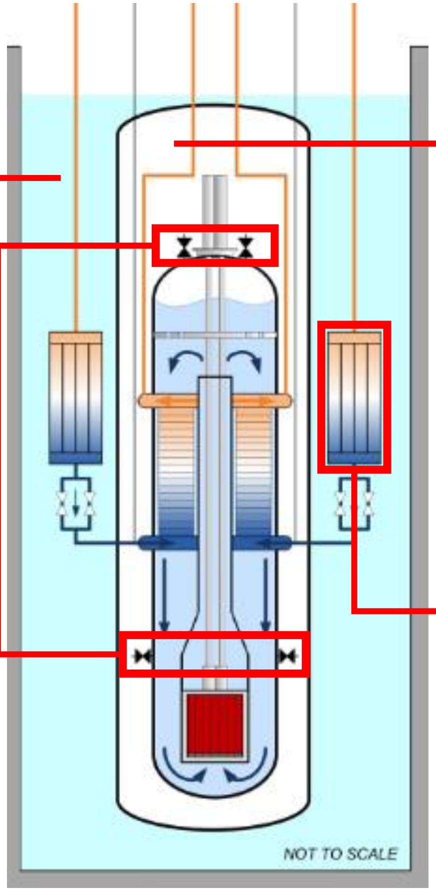
Thank you for your attention

E-mail: hjan97@hanyang.ac.kr

ATHENA

NuScale passive safety system

Common pool (CP)
- 12 modules submerged in the CP



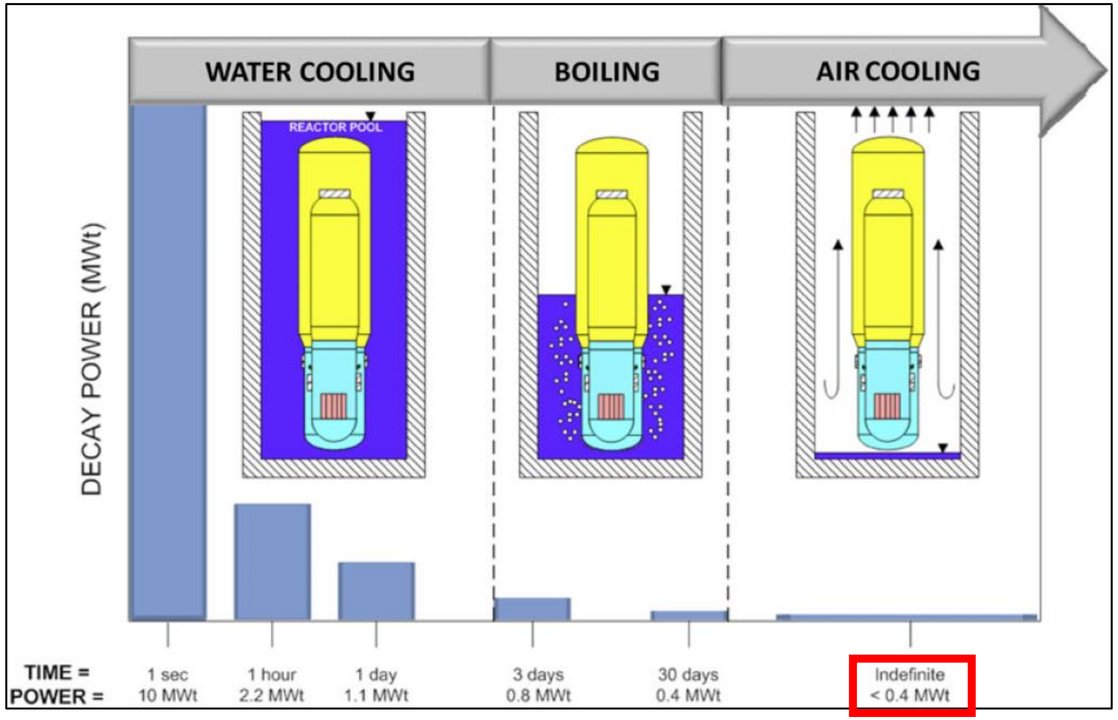
Containment vessel (CNV)
- Containing reactor pressure vessel (RPV)
- Weakly vacuumed vessel
- To prevent
  1. Heat loss from RPV
  2. Hydrogen flammability

DHRS
- Heat removal through SG

ECCS
- Steam injection into the CNV
- Recirculation of condensate
- Heat removal to common pool

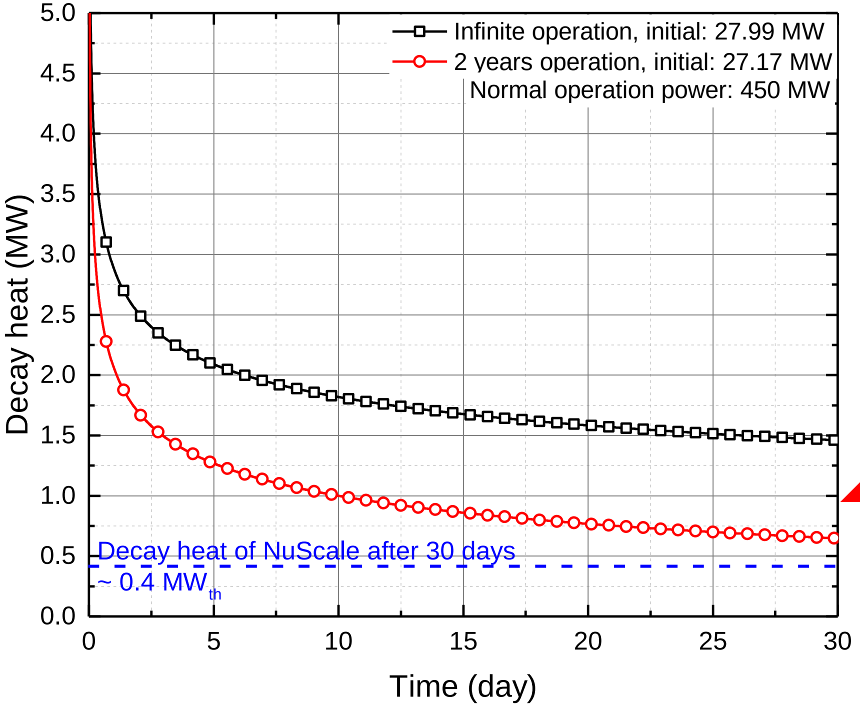
1) Reyes Jr, José N. "NuScale plant safety in response to extreme events." Nuclear Technology 178.2 (2012): 153-163.
2) NuScale Power, Status Report - NuScale SMR (NuScale Power, LLC), 2020.

Appendix. B
Safety system of NuScale and its limitation



Long-term coolability

- Boiling induced by the decay heat
  → water level decrease
- Water depletion after 30 days
- **0.4 MWt is sufficiently low for air cooling → indefinite grace period**

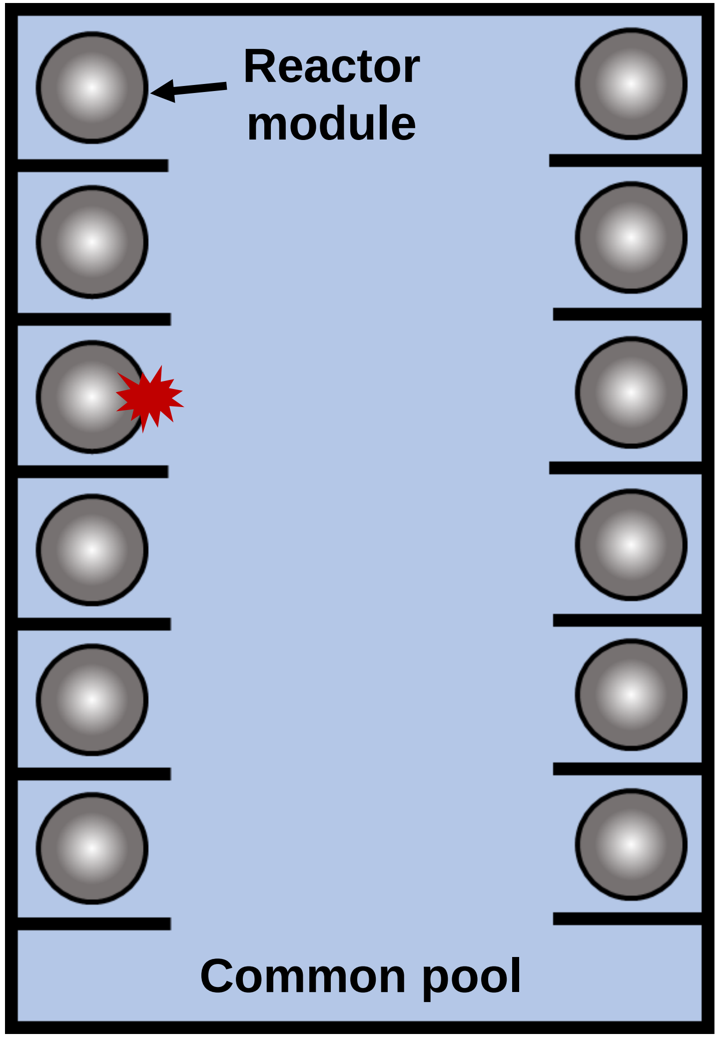


- **Larger thermal power → lager CP inventory requirement**
- Improvements required for **high-powered reactors**

1) Reyes Jr, José N. "NuScale plant safety in response to extreme events." Nuclear Technology 178.2 (2012): 153-163.
2) Park, Jae Hyung, et al. "Lumped Analysis of Effective Long-term Coolability by Using Flooding Safety System for Small Modular Reactors." (2021)

Appendix. B

Safety system of NuScale and its limitation



Additional limitations

- Heat loss to CP
- Difficult approach for management
- Inadvertent interfering effects of accidental module to others

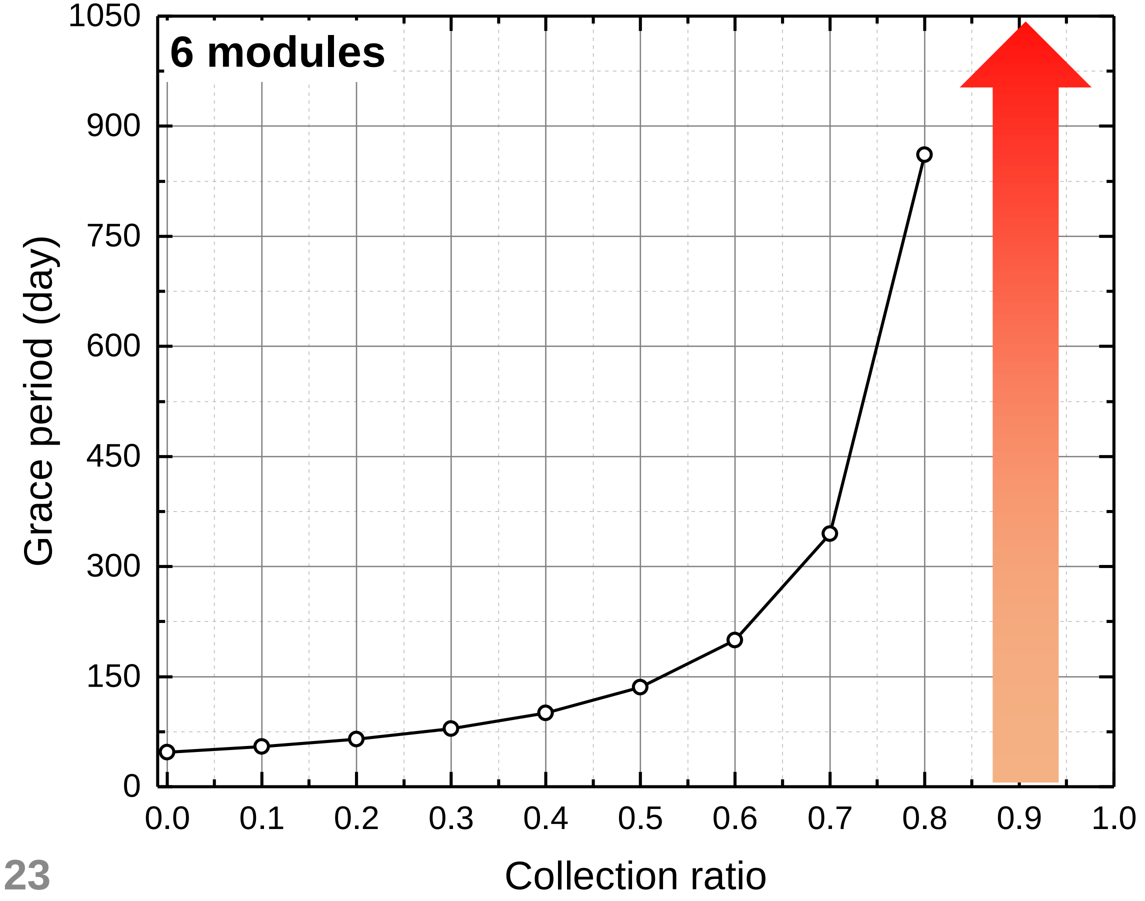
Requirements to improve the system

- **Separate and dry cavities during normal operation**
- Additional passive safety system for **enhanced long term coolability**

ATHENA

Lumped analysis for long-term coolability of FSS

Grace period with partial re-collection ratio



Conclusion

- Higher re-collection ratio → Longer grace period
- Indefinite grace period with collection ratio 1.0

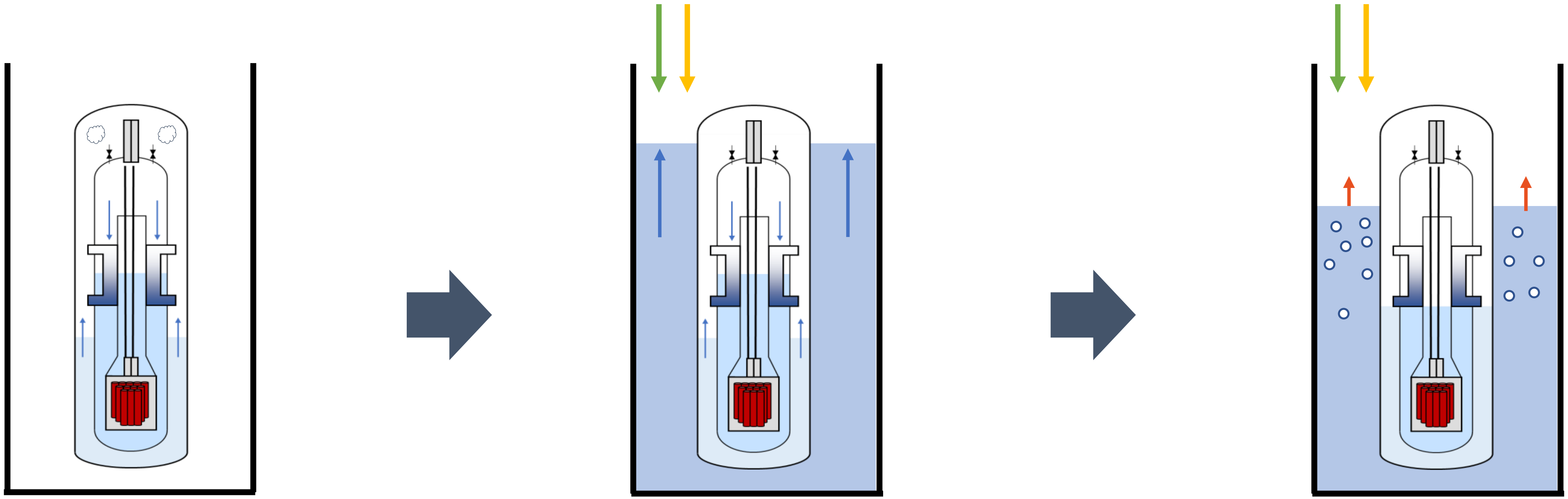
Limitation

- Immediate flooding was assumed
- **Insufficient flooding rate may result in core damage**

1) Park, Jae Hyung, et al. "Lumped Analysis of Effective Long-term Coolability by Using Flooding Safety System for Small Modular Reactors." (2021)

ATHENA

Accidents involving Overpressure of RPV



- RPV overpressure
- Reactor vent valves open
- Steam injection into the CNV

- Flooding of the cavity
- Steam condensation in the CNV
- Re-supply of the condensate into RPV through recirculation valves

- Boiling of cavity coolant
- Continuous coolant supply from condensation system

HANYANG UNIVERSITY

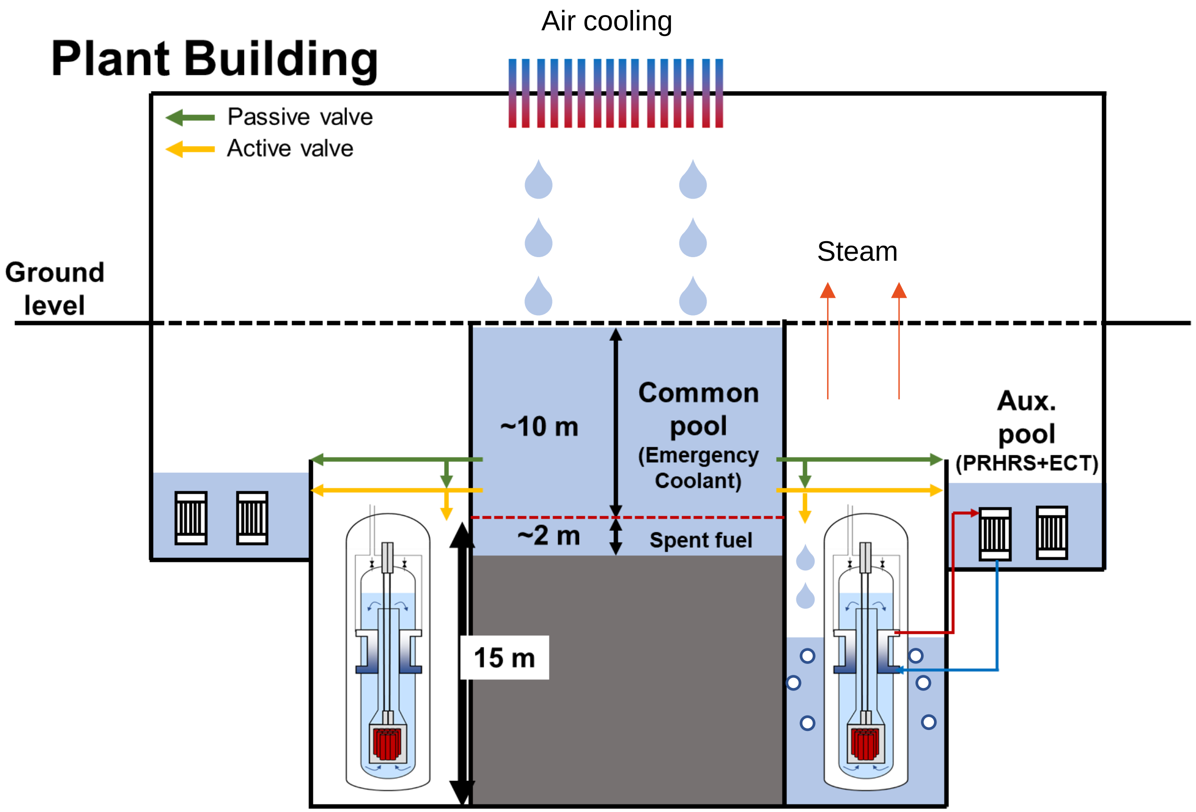
Introduction

Objective of flooding safety system

Flooding system

Separated cavity

Long-term coolability



Evaporation → Condensation → Re-collection → Re-supply

Enhanced long-term safety!